Fisheries and Oceans Science | Pêches et Océans Sciences

CSAS

Canadian Science Advisory Secretariat

Research Document 2001/085

Not to be cited without permission of the authors *

SCCS

Secrétariat canadien de consultation scientifique

Document de recherche 2001/085

Ne pas citer sans autorisation des auteurs *

Preliminary Studies of Density Stratification and Fluorescence on the Newfoundland Shelf

Études préliminaires de la stratification de densité et de la fluorescence sur la plate-forme de Terre-Neuve

J. D. C. Craig, E. B. Colbourne and G. L. Maillet

Department of Fisheries and Oceans
P. O. Box 5667
St. John's Newfoundland, Canada A1C 5X1

* This series documents the scientific basis for the evaluation of fisheries resources in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

* La présente série documente les bases scientifiques des évaluations des ressources halieutiques du Canada. Elle traite des problèmes courants selon les échéanciers dictés. Les documents qu'elle contient ne doivent pas être considérés comme des énoncés définitifs sur les sujets traités, mais plutôt comme des rapports d'étape sur les études en cours.

Research documents are produced in the official language in which they are provided to the Secretariat.

Les documents de recherche sont publiés dans la langue officielle utilisée dans le manuscrit envoyé au Secrétariat.

This document is available on the Internet at: Ce document est disponible sur l'Internet à:
http://www.dfo-mpo.gc.ca/csas/

ISSN 1480-4883
Ottawa, 2001

Canada

Abstract

Fluorescence, salinity and temperature data were examined for station 27 and the Flemish Cap transect on the Newfoundland Shelf. Anomalies calculated for the density stratification based on monthly means and harmonic regressions yielded similar results. Alternative methods of determining the degree of stratification and estimating the mixed later depth were explored and compared. Both temperature and salinity contribute significantly to the annual cycle in stratification on the Newfoundland shelf, however the variation in salinity was primarily responsible for the recent increasing trend in the observed stratification. The timing of the spring bloom coincided with the onset of stratification at station 27.

Representative fluorescence and density data were compared on temporal and spatial domains.

Résumé

Des données sur la fluorescence, la salinité et la température recueillies à la station 27 et le long du transect du cap Flamand, sur la plate-forme de Terre-Neuve, sont examinées. Les calculs des anomalies de la stratification de densité basés sur les moyennes mensuelles et des régressions harmoniques ont donné des résultats semblables. D'autres méthodes de détermination du degré de stratification et d'estimation de la hauteur de la couche de mélange sont examinées et comparées. Tant la température que la salinité contribuent nettement au cycle annuel de stratification sur la plate-forme de Terre-Neuve, bien que la variation de la salinité est principalement responsable de la récente tendance à la hausse de la stratification observée. L'apparition de l'efflorescence planctonique printanière a coïncidé au début de la stratification à la station 27.

Des données représentatives sur la fluorescence et la densité sont comparées au plan temporel et spatial.

Introduction

The Atlantic Zonal Monitoring Programme (AZMP) was developed to improve the capacity to describe, understand, and forecast the state of the marine ecosystem. At the most basic level in achieving these objectives, it is important to have a data set of sufficient completeness and to observe interrelations between the fundamental physical quantities such as salinity, temperature and nutrient concentrations and the population of phytoplankton and zooplankton in the water column. The well-known spring bloom with the onset of stratification is but one of perhaps several mechanisms by which the biological activity and the density structure of the water column are interrelated. The purpose of this paper is to suggest a starting point towards understanding these ecosystem interactions in the context of indices that are derived from raw oceanographic data. We outline continuing studies on the development of environmental indices that are related to the density structure of the water column and attempt to compare these on temporal and spatial domains with fluorescence, a commonly used proxy of biological activity in the water column.

Much work has been done towards developing understanding the interactions between the physical and biological processes in the ocean. In the 1930s, Gran first described a link between the spring bloom and the density structure of the water column. As outlined by Mann and Lazier, (1996 and references cited therein) Gran observed that a sudden increase in Plankton occurred during the spring. This effect was later quantified by Sverdrup (1946,1953) and is now known as the spring bloom. Recently, the Sverdrup model has been reconsidered, for example Platt et al. (1994) and further investigations are likely to be fruitful in view of the improved instrumentation and the increased amount of data that has become available since Sverdrup's time. That stratification affects vertical mixing and vertical transport of nutrients and primary production is well documented. Stratification can have a profound effect on biological activity, for instance Erbacher et al. (2001). It is important that efforts continue to better understand the role of stratification in primary production. Alternately, biological processes can affect the dynamics and structure of the water column, Edwards et al. (2001).

Several methods have been used to express the stratification of the water column quantitatively. Brainerd and Gregg (1995) examined the fine structure using free falling instruments and compared several definitions of mixed layer and mixing layer depths. These include the depth at which the density reaches a threshold greater than that of the surface water or the depth at which the gradient of either temperature or density reaches a specified value. Typical values for these criteria were 0.05 kg m^{-3} and 0.05 kg m^{-4}, respectively. More recently, Kara et al. (2000) developed methods for determining isothermal layer depth and mixed layer depths and compiled a critical evaluation of criteria used to estimate the isothermal and mixed layer depths. Thomson and Fine (2001) explored a 'split and merge' algorithm to study the density structure. They partitioned the variability of the mixed layer depth into annual, seasonal and diurnal constituents and accounted for most of the variability of the density structure.

In the present paper, the stratification index as used by Drinkwater et al. (1999) is compared with a maximum gradient method that we have been exploring. Where the availability of data permits, we attempt to relate the stratification with fluorescence in terms of the annual and long-term time and spatial domains. We examine the origins of the annual stratification signal and its long-term trend.

Sources of data

Much of data for this analysis was obtained from the Northwest Atlantic Fisheries Centre (NAFC) database, the Marine Environmental Data Service, the Bedford Institute of Oceanography and Memorial University. Station 27 data at standard depths was obtained from the station 27 atlas maintained at the NAFC. Sampling at station 27 before the 1980s was usually at the standard depths of 0, 10, 20, 30, 50, 100, 125, 150 metres and the bottom. From about 1990 to present, sampling was at intervals of approximately 20 cm, as determined by the deployment speed of 50 metres/minute and the instrument sampling frequency of 8 Hz, and some degree of quality control of the raw data. The accuracy of the measurements was maintained to within 0.005°C for temperature and 0.005 Seimens/metre or better, for conductivity. Pressure measurements were accurate to 0.25 percent or better. Fluorescence measurements were accurate to 3 percent on a relative scale.

Station 27 has been sampled approximately 50 times a year in recent years. The standard transects were sampled three times a year for much of the past decade.

Analysis

Stratification at station 27

The stratification index was calculated using a method similar to that of Drinkwater et al. (1999). Because the high variability in temperature and salinity in the upper layer of the water column, it was desirable to sample the surface layer at some depth beneath the surface, usually 5 metres. The surface density was taken nearest but less than or equal to than 5 metres. The other was the first available density falling between 48 and 53 metres for a given profile. The gradient was calculated as the quotient of difference in densities and the difference in the corresponding depths. A time series of the stratification index, Fig. 1, shows the annual cycle and a general increase in its amplitude over the past decade.

This feature also appeared in the time series of the anomaly in the stratification index. Two methods were used to calculate the anomaly. The first method was based on determining the annual signal in the reference period (1961-1999 per the World Meteorological Organisation and North Atlantic Fisheries Organisation standards) based on the monthly mean value of the stratification index as calculated on a cast by cast basis for each month of the year. The second method used a harmonic regression of the data in the reference period to construct a mean annual signal.

To calculate the monthly mean anomaly, all available stratification indices for each month in the reference period were averaged. The anomaly was calculated by subtracting these values from the corresponding monthly means of all data from 1950 to 2000. From the monthly means, a yearly mean was calculated which was filtered by a five year running mean, Fig. 2.

The following expression was used to determine the harmonic mean annual cycle of the stratification index:

$$y(x) = \bar{y} + \sum_{i=1}^{N} A_i \sin(i\omega x - \varphi_i)$$

where $y(x)$ is the stratification index at day-of-the-year x, ω is the fundamental harmonic frequency of 1yr^{-1}, $\bar{y}$ the aperiodic component and A_i and φ_i are the respective amplitudes and phase angles. It was computationally expedient to express this as an equivalent formulation in terms of the sum of sine and cosine terms of the fundamental and higher harmonics. This was achieved using in-house routines by which values for the aperiodoic component and the coefficients of the sine and cosine terms were found and used to construct a mean annual cycle for the 1961-1999 reference period. An anomaly time series was calculated by subtracting the value of the annual cycle at the day of the year corresponding to each of the observations in the time series of stratification indices. After some experimentation with different values of N, it was determined that an optimal fit was obtained when four harmonics were used; lower values gave a poor fit, and higher values resulted in spurious high frequency components appearing in the annual cycle curve. In addition, the time series anomaly appeared to converge for N =4 because invoking additional harmonics did not appreciably change the appearance of the plot. This result differed from that of Aikenhead (1987) who found the 4th harmonic was not a significant factor.

Comparing Figs. 2 and 3 showed the monthly means and harmonic regression methods gave very similar results although the harmonic anomalies are about 10 percent greater.

To determine the effect of the method of averaging on the appearance of the anomaly time series, the harmonic anomalies, which are calculated on a daily time scale, were low pass filtered by 25 iterations of a 5 point Savitsky-Golay smoothing procedure. An oscillation was evident in the time series for the interval

1990-2000, a period of relatively high sampling frequency, Fig. 4. It had a period of one year and was consistent with a residual annual signal in the stratification anomaly arising from greater-than-normal stratification over the past decade. This oscillation was not as readily apparent in the in the monthly averaged time series because of the higher level of noise.

It should be noted that station 27 was not occupied on a regular basis. This may have biased the regression curve because the annual signal was not uniformly represented by the data, especially prior to 1990.

It is clear from this analysis that the stratification at Station 27 has been generally increasing since 1990. This is consistent with the findings on the Scotian shelf (Drinkwater et al. 1999) and those of Thompson and Fine (2001) who have observed a steady decline in the mixed layer depth over the same period. The timing of the maximum in the stratification index increased by one day as the reference period was changed from 1961-1990 to 1971-2000, the amplitude in the latter was about 7 percent greater, consistent with increased stratification observed in the 1990s.

Alternate methods of estimating stratification and the mixed layer depth

Much of the historic data is available only at standard depths. In recent years, data of much higher resolution has become available. This motivated a study to determine if a more representative calculation of stratification could be had by employing all of the data in a given CTD cast rather than simply the density at two points. This approach involved calculating numerical derivatives and curve fitting to data in the 1992-2000 period for which higher resolution data were available.

In principle, it should be possible to calculate the derivative of density with respect to depth using numerical methods. In practice, because the density profile is inherently noisy, this derivative is often poorly defined. For this reason, some degree of smoothing must first be applied to the raw density data before the derivative taken. Additional smoothing may be applied to the derivative so that its maximum and the corresponding depth are more clearly defined. Treating the density data with a simple running mean filters proved adequate for almost all CTD data casts at station 27 for which high resolution data were available, Fig. 5.
The magnitude of the maximum gradient, and to a lesser extent, the depth at which it presented showed some degree of sensitivity to the box-car size and the number smoothing cycles.

To avoid the need for arbitrary selection of smoothing parameters and methods of implementation, a curve was fitted to the data by least squares regression and the derivative of the curve was calculated analytically. Simple polynomials were tried, i.e.:

$$y = a_n x^n + a_{n-1} x^{n-1} \Lambda + a_0$$

where y is the value of the density at depth x and n is the degree of the polynomial. This can be written as:

$$y = \sum_{i=0}^{n} a_i x^i$$

from which the analytical derivatives may be written:

$$y' = \sum_{i=1}^{n} i a_i x^{i-1}$$

$$y'' = \sum_{i=2}^{n} i(i-1) a_i x^{i-2}$$

The depth of the maximum gradient, z_{max} was taken as the value of x for which $y'' = 0$. The magnitude of the maximum gradient was found by evaluating y' at $x = z_{max}$.

A 7th degree polynomial gave a reasonable fit for all but the upper few metres in relatively highly stratified profiles, Fig. 6. Thomson and Fine (2001) obtained a good fit over the entire column by using composite functions, but the procedure was more complex.

The numerical and analytical methods of evaluating the degree of stratification offer an advantage over the calculation of the stratification index in providing an additional index, namely the depth of maximum gradient.
Although this number refers strictly to the depth of the middle of the pychnocline, it is reasonable as an estimate or at least a proxy of the mixed layer depth.

Discordant indices have resulted from particularly noisy data or for data obtained in the winter period where the inflection point in the density profile was poorly defined, but other methods of estimating the stratification index and mixed layer depth were similarly afflicted. The value of the maximum gradient was generally about an order of magnitude greater than the two-point stratification index. Because of its apparent sensitivity to the fine structure features in the water column such as internal waves, diurnal processes and turbulence at the mixing layer (Brainerd and Gregg, 1995), the maximum gradient and its corresponding depth exhibit greater variability than the stratification index. This is the subject of continuing investigation.

A comparative study of the time series of the stratification index with indices derived from the gradients of the density profiles over the past 12 years was gave consistent results. The maximum in the annual stratification cycle occurred in mid August (day $233 \pm 2\%$) for both methods using data from the past 12 years.

The role of temperature in stratification

Our data shows evidence that the stratification index is on an increasing trend in recent years, consistent with the observations of Drinkwater et al. (1999) who found that this increase in stratification was principally a response to lower surface salinities. In view of the general increase in both summer temperatures and salinities over this period, Figs. 7 and 8, we were motivated to examine the role of temperature in stratification on the annual and decadal time scales. The annual signals of salinity and temperature were plotted on a standard TS diagram, Fig. 9. This showed that while the variation in density of the water at 50 metres was driven essentially by changes in the salinity, the surface water density changes were driven by almost equal contributions from temperature and salinity changes. Therefore, the annual cycle in stratification, Fig. 2, is driven by both variations in temperature and salinity. It was noted that annual signal in the stratification index was enhanced by a phase lag in the density cycle at 50 metres. This was because in August, the minimum density of the surface water occurred with a maximum density at 50 metres.

To investigate the origin of the increase in the stratification anomaly, the annual signal of the surface temperature and salinity for data in the 1990-2000 period were plotted on the same TS axes. A shift of the annual cycle curve of approximately -0.2 salinity units with very little change in the temperature signal supports the finding that the increase in stratification during the 1990's originates with reduced surface salinities, consistent with similar findings on the Scotian Shelf by Drinkwater (1999).

Temporal links between stratification and fluorescence

Since 1992, sampling of fluorescence for station 27 was done on a more regular basis. A time series of this data, Fig. 10, showed coherence in the annual cycles of integrated density and fluorescence. The high variability in the amplitude of the fluorescence signal was likely associated with the limited sampling regime and the short duration of the spring bloom. For instance, the station may have been sampled near the peak of the spring bloom some years, giving a large peak, and sampled at more quiescent times in other years, resulting in smaller peaks.

Contour plots of monthly means (averaged over 1992-2000) were prepared for density and fluorescence, Figs. 11,13 and clearly show the formation of the spring bloom in advance of the peak of stratification. A

small signal appeared in the fluorescence in September that suggested a fall bloom, and both the spring and fall periods had increased levels of fluorescence at depths considerably below the mixed layer, consistent with sinking of fluorescent matter from euphotic zone. The bulk of the fluorescence signal was constrained between the surface and 30 metres. The density gradient with respect to depth, Fig.12, shows a seasonal maximum coinciding with the minimum surface density in August, and maximum degree of stratification to occur at the same time from 10 to 20 metres in the water column.

Higher resolution of the density time series, Fig. 14 shows that the isopycnals are moving up in the water column immediately before the onset of the spring bloom, Fig. 15.

Harmonic regressions and monthly means were calculated for the stratification index and the integrated fluorescence in the 1992-2000 period, Fig 16. Increasing the number of harmonics beyond three increased the discrepancy between the regression curves and the monthly means. The fluorescence regression curve clearly shows the spring bloom peaking near day 100 and evidence of a fall bloom near day 250. At about day 60, the derivative curve crossed the zero point corresponding to the yearly minimum in the degree of stratification. This coincided with the start of the spring bloom. The rate of stratification peaked just before day 200.

The expanded plot, Fig. 17, for the same data in the winter and spring indicated that the spring bloom is timed with the onset of stratification. The peak of the spring bloom precedes an increase in the rate of stratification development in the water column. This appeared to suggest that stratification was responding to increased biological activity. It has been shown by Edwards et al. (2001) that the presence of chlorophyll can influence heating rates of water on the Scotian Shelf. No evidence of this effect was apparent in the historical temperature data for Station 27. The water column was essentially isothermal at the depth range and period corresponding to the peak in the spring bloom.

Spatial relationships

A reasonably persistent trend in the density and fluorescence along the standard transects of the Newfoundland shelf has been observed. Fig. 18, prepared from 1999 summer data was representative of the recent data (1992-2000) of the Flemish Cap transect. Data prior to this period did not have sufficient depth resolution to permit calculating the derivatives. Although these results were noisy, especially the gradient calculation, there was evidence of a decrease in the magnitude of the maximum density gradient, an increase in the depth at which it occurs and a decrease in the value of the stratification index with increasing distance from the coast. This was accompanied by an increase in the fluorescence signal, Fig. 19. We have tentatively ascribed this trend in the density structure to the advection of fresh water from the coast, although more elaborate mechanisms such as the effects of bottom topography may be involved, for example, Gawarkiewicz (2000).

Conclusions

Annual cycles of stratification index that were calculated from monthly means and harmonic regression of data in the standard reference period were very similar in phase and amplitude. The optimal number harmonics for the regression of the 1961-1990 data was 4. An increasing trend was observed in the amplitude of the annual signal of the stratification index and stratification anomaly for the past decade.

Alternate methods of calculating stratification from density profiles were investigated. Numerical differentiation gave consistent results but required treatment of the data before and after differentiation to yield a clearly defined maximum in gradient. Fitting a function to the data eliminated the need for an arbitrarily selected smoothing routine and gave a uniquely defined maximum gradient and corresponding depth. The maximum gradient method appeared to be sensitive to small-scale processes in the water column and yielded values with greater variability than the stratification index during the winter.

The annual signal in stratification arose from changes in the salinity and temperature of the surface water. Summer stratification indices were increased by a phase lag in the seasonal density cycle at 50 metres.

Reduced salinity of the surface water appeared to be driving the increase in the stratification index over the past decade.

A spring bloom preceded the peak of stratification at station 27, but reached its maximum in its annual cycle at the onset of stratification. Higher levels of fluorescence were seen with lower degrees of stratification, which decreased with distance from the coast for the Flemish Cap transect. This trend was observed over several years.

Acknowledgements

Helpful discussion with Brad de Young, Ken Drinkwater, Erica Head, Jim Helbig, Pierre Pepin and Len Zedel is gratefully acknowledged. We are very grateful to the technicians and students who assisted with the data acquisition, processing and archiving.

References:

Aikenhead, S. A., Temperature and Salinity off Newfoundland: Station 27 Annual Cycle and Residuals, NAFO SCR Doc 87/66, 1987

Brainerd, K. E., and M.C. Gregg, Surface mixed and mixing layer depths, Deep Sea Res. 1, 42, 9, 1521-1543, 1995

Drinkwater, K., E. B. Colbourne and D. Gilbert, Overview of Environmental Conditions in the Northwest Atlantic in 1998, NAFO SCR Doc. 99/36, 1999

Erbacher, J., Brian T. Hubert, Richard D. Morris, and Molly Markey, Increased thermohaline stratification as a possible cause for an ocean anoxic event in the Cretaceous period, Nature, 409, 325-237 2001

Mann K. H., J.R.N. Lazier, Dynamics of Marine Ecosystems, K.H., Blackwell Sciences Inc., 1996

Gawarkiewicz, Glen. Effects of ambient stratification and shelfbreak topography on offshore transport of dense water on continental shelves. J. Geo. Res. 105 C2 3307-3324 2000

Kara, A. B., Rochford, P.A., and Hurlburt, H. E., An Optimal Definition for Mixed Ocean Layer Depth J. Geo. Res. 105,C7, 16803,16821, 2000

Sverdrup, H. U. 1953. On conditions for the vernal blooming of phytoplankton. J. Cons. perm. int. Explor. Mer., 18: 287-295.

Sverdrup et al. 1946. The Oceans, their Physics, Chemistry and General Biology. Prentice Hall, NY,1087 pp.

Platt, T., J.D. Woods, S. Sathyendranath and W. Barkmann. 1994 Net primary production and stratification in the ocean pp 247-254 In Johannessen, D.M. Muench and D.E. Overland. The Polar Oceans and their Role in shaping the Global Environment. Geophys. Monograph 85 AGU Washington 525 pp.

Thomson, R. E. and Fine, I.V., Estimation of mixed layer depth for the Vancouver Island continental margin, Submitted to J. Phys. Ocean. 2001

Edwards, A.M., Trevor Platt and D.G. Wright, Biologically induced circulation at fronts, J. Geo. Res. 106, C4 7081-7095, 2001

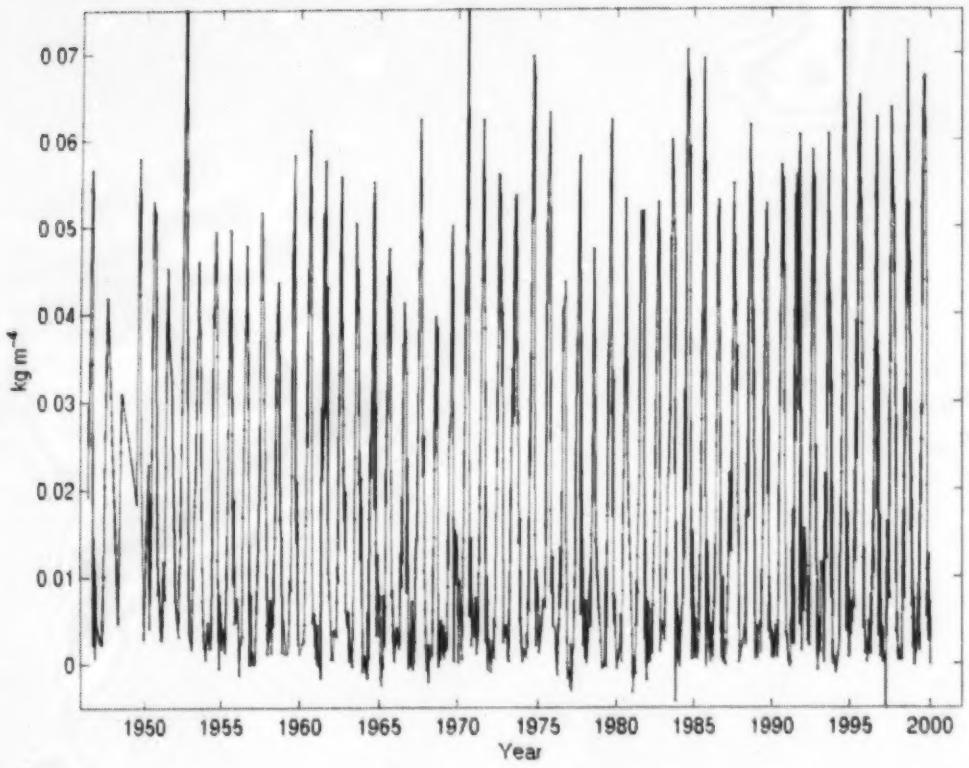

Fig.1. Time series of the stratification index at Station 27 (47° 32.8'N 52° 35.2'W)

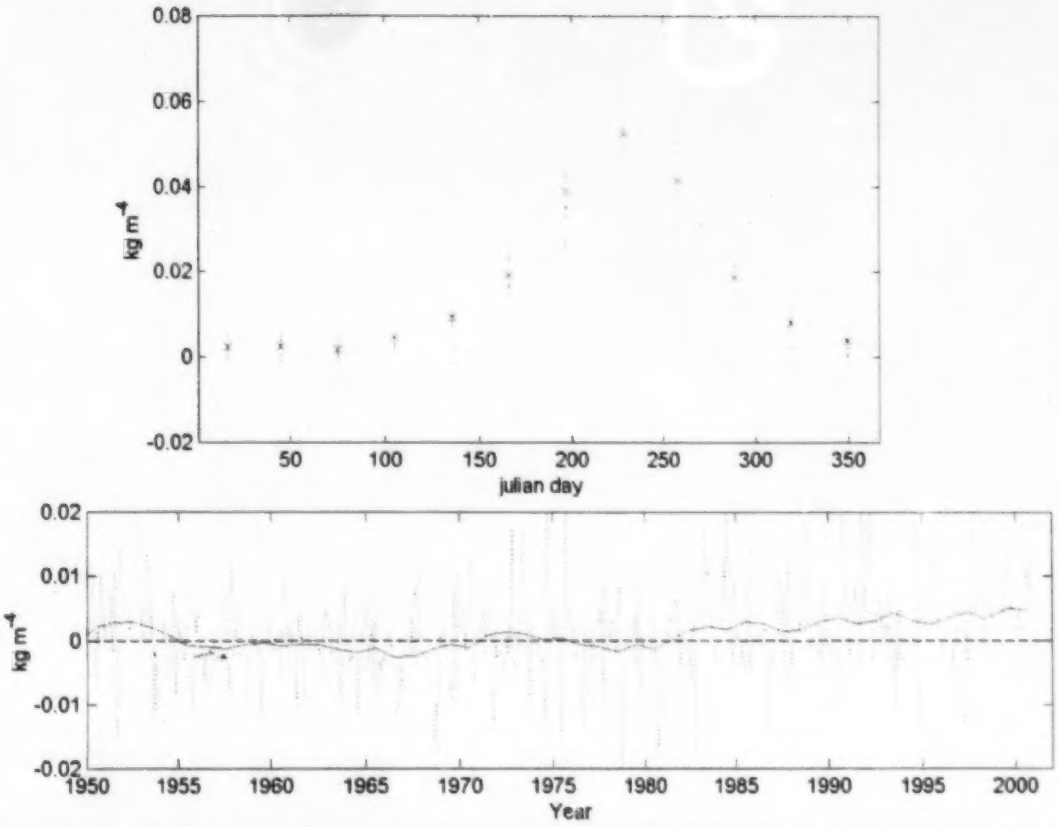

Fig.2. Annual monthly cycle of the stratification index for the 1961-1990 reference period and the time series of anomalies of monthly means (dotted line). The solid line is a 5 year running mean of annual anomalies.

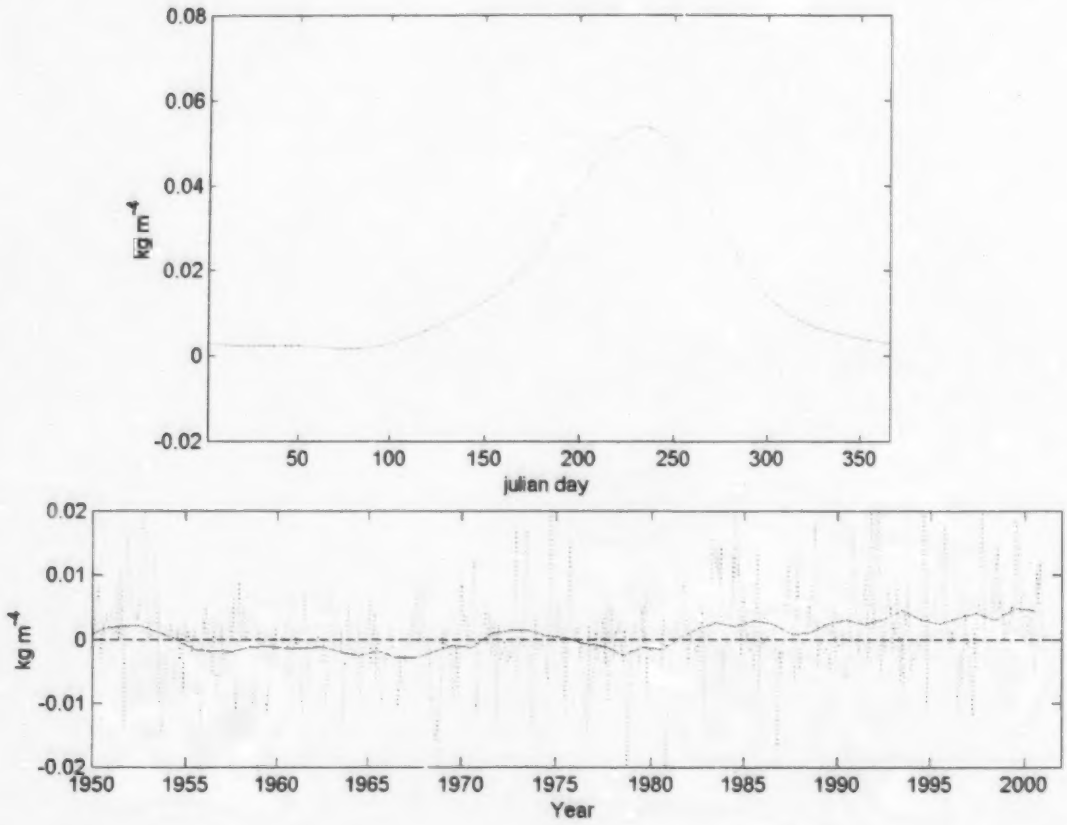

Fig.3. Harmonic regression of stratification index at station 27 and anomaly time series.

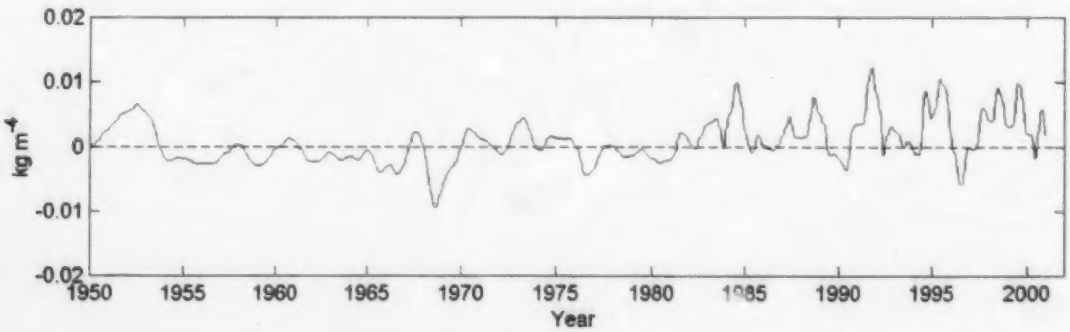

Fig.4. Harmonic anomaly time series, low pass filtered.

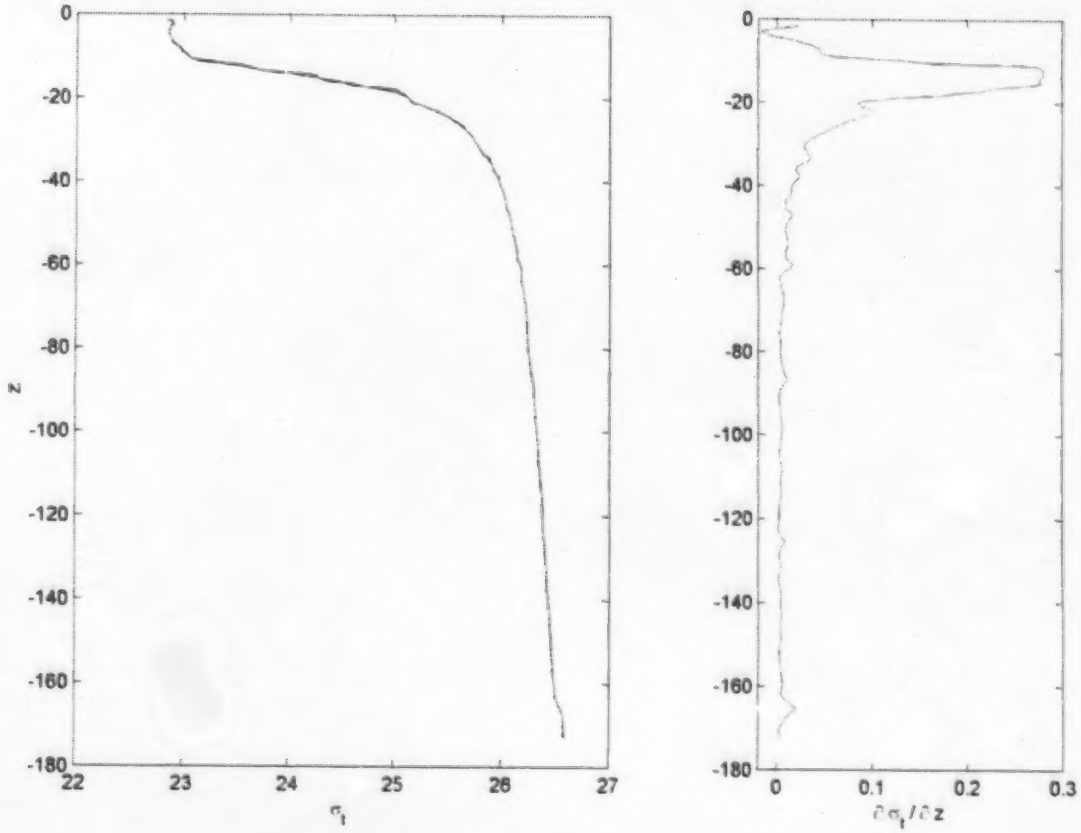

Fig.5. Numerical differentiation of density with respect to depth. The data and derivative have been filtered with 20 iterations of a three-point smoothing routine.

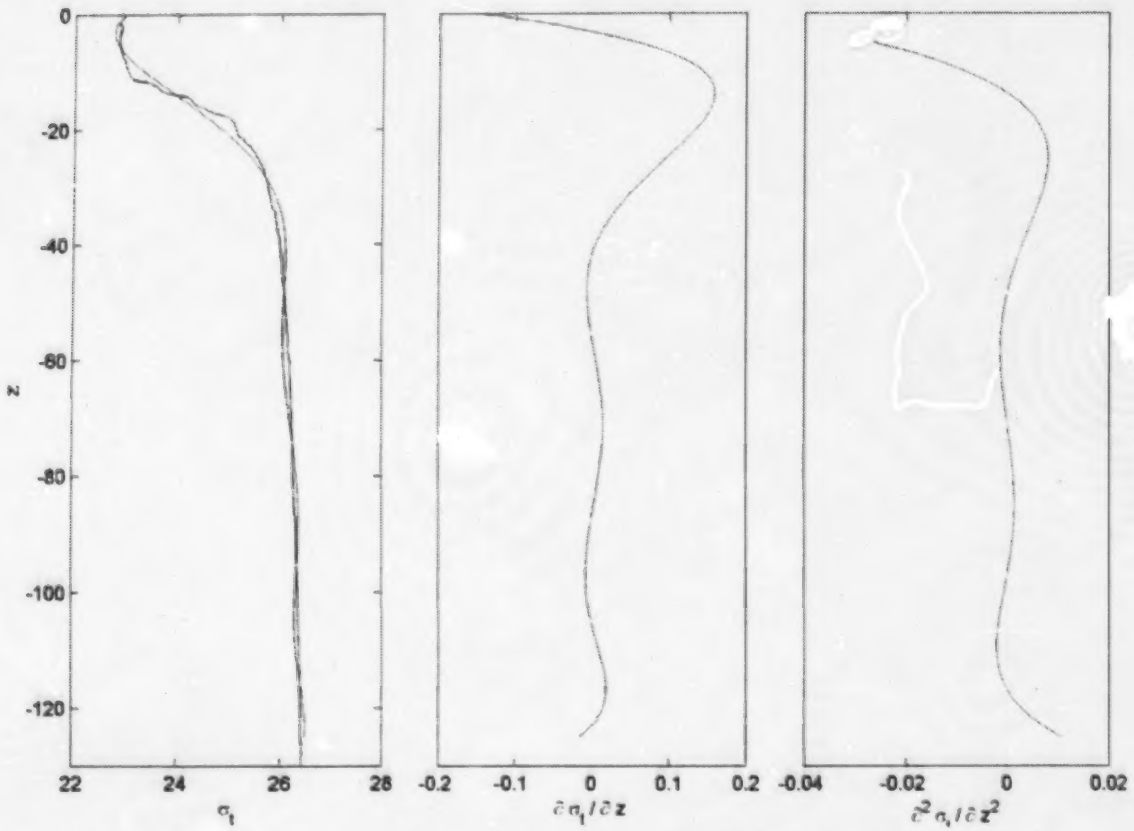

Fig.6. Polynomial regression of the density profile and calculation of the analytical derivatives. The inflection point of the density profile is the depth of maximum gradient. This depth, 13.9m was found by equating the second derivative to zero. The maximum value of the gradient was 0.153 kg m^{-4}

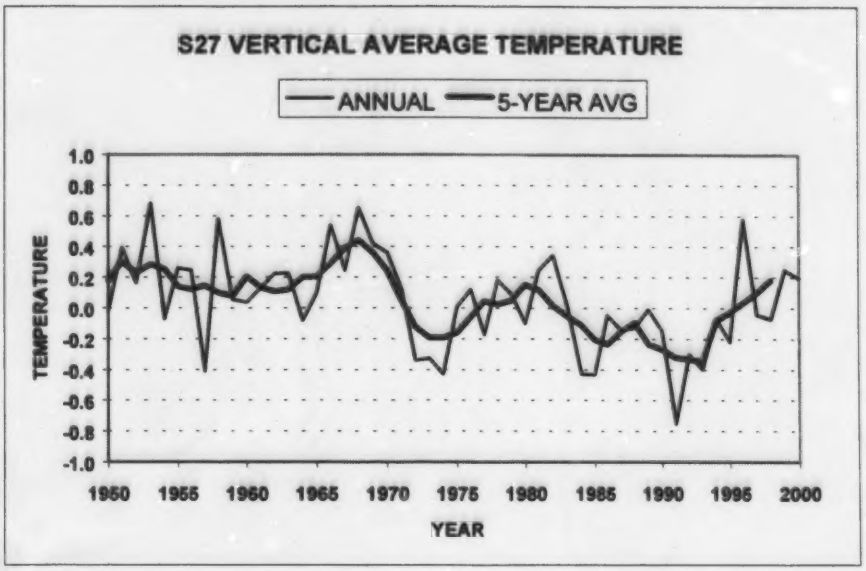

Fig.7. Vertically averaged summer temperature anomaly.

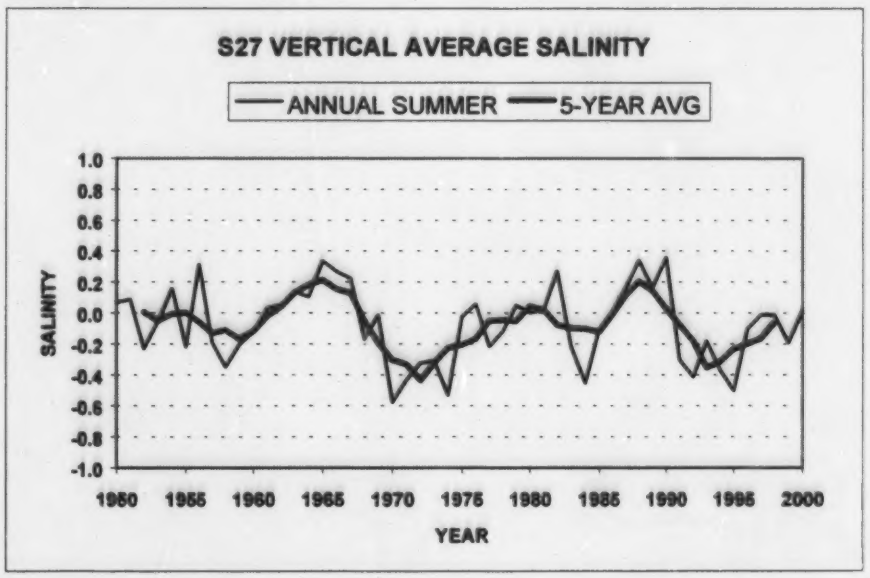

Fig.8. Vertically averaged salinity anomaly.

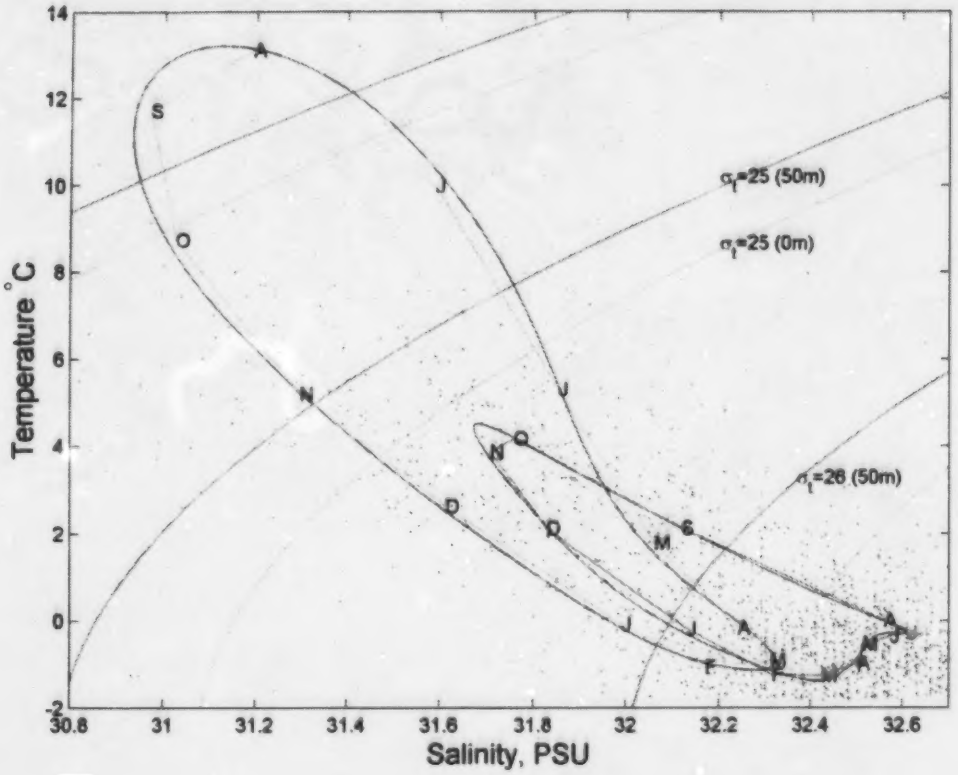

Fig.9. TS diagram for station 27 for the surface and 50 metre levels, based on the 1982 UNESCO equation of state. The letters indicate the months of the year. The dark annual cycle curves were obtained from harmonic regressions of the T and S data.

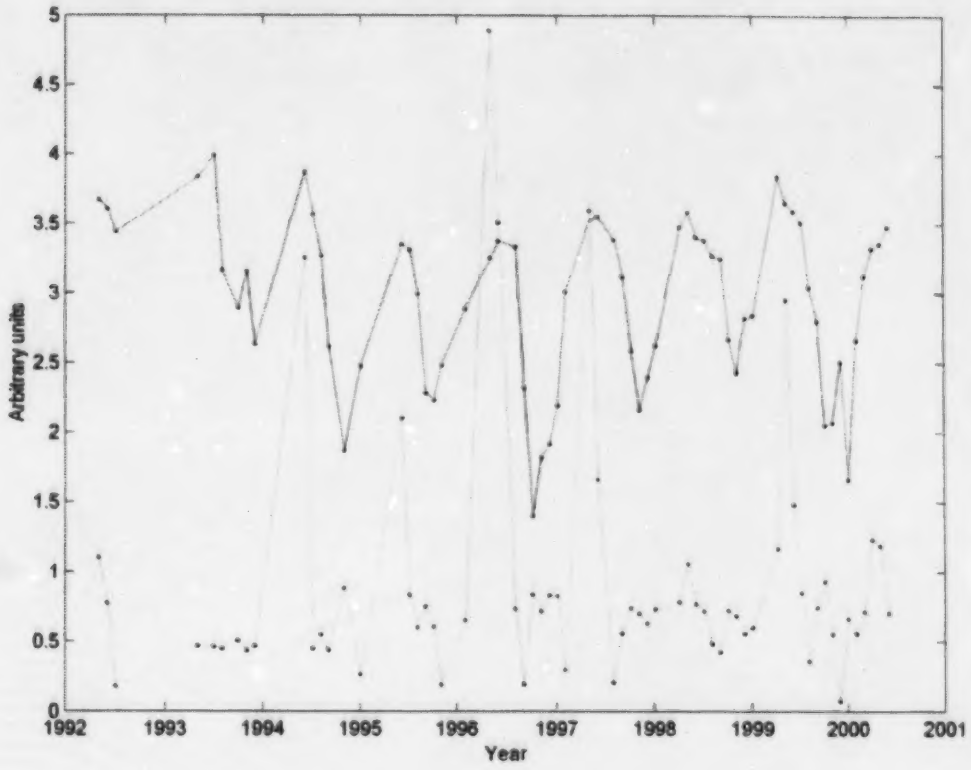

Fig.10. Integrated monthly density (top) and fluorescence, station 27.

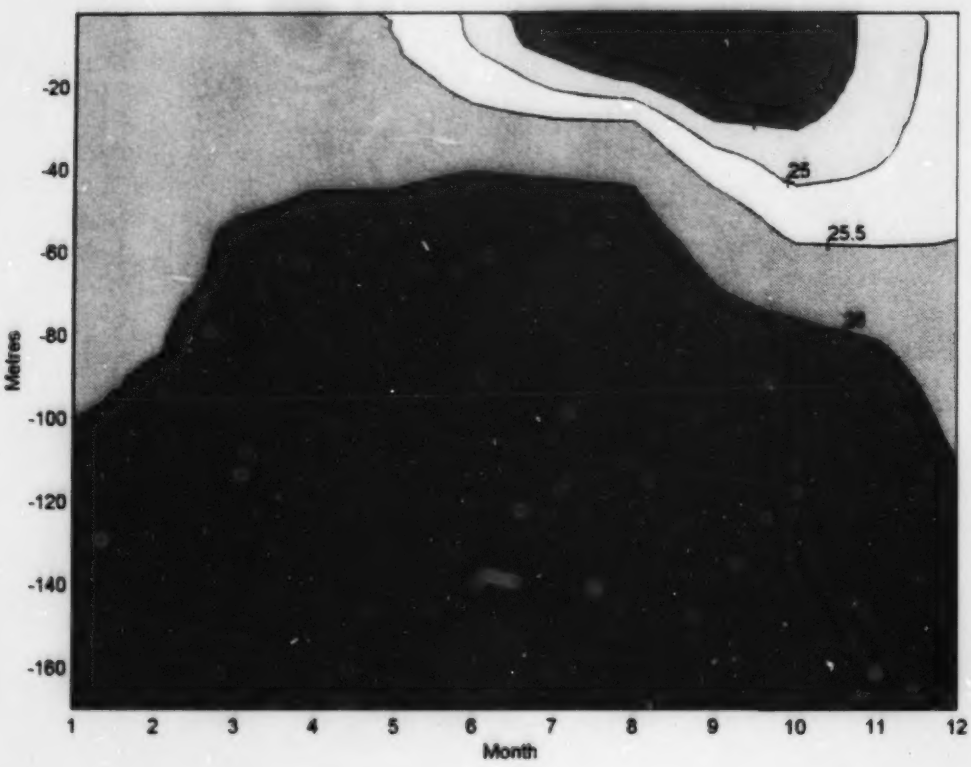

Fig.11. Density time series contour at Station 27 for 1992-2000.

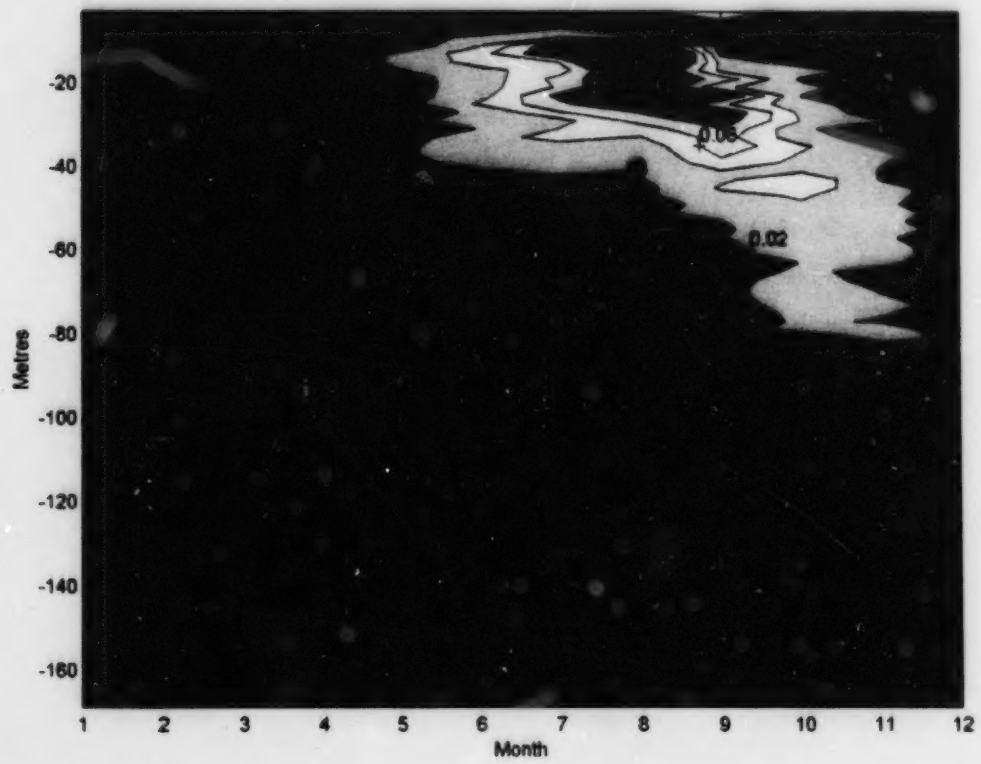

Fig.12. The gradient of density with respect to depth for station 27, 1992-2000.

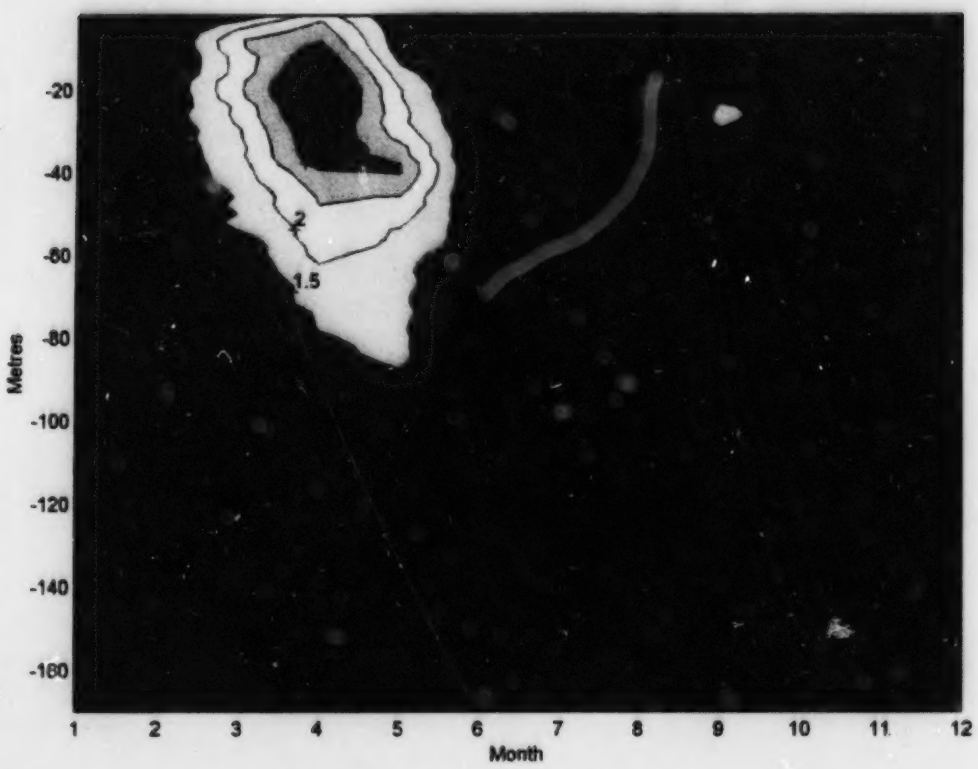

Fig.13. Fluorescence time series contour at Station 27 for 1992-2000.

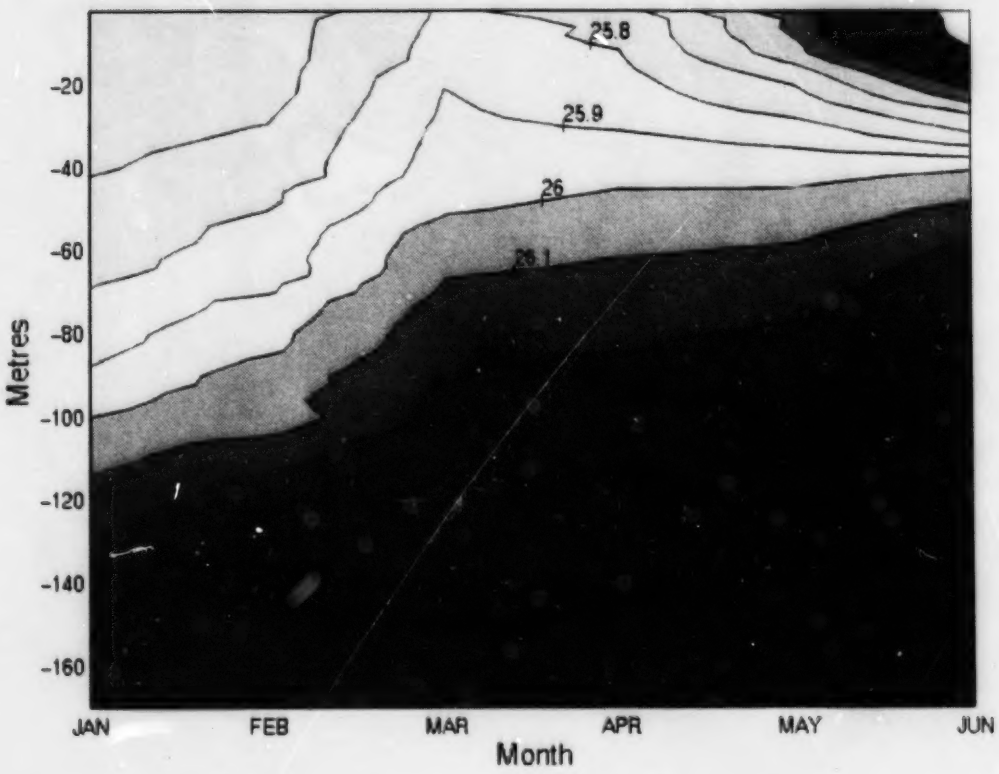

Fig.14. Density time series at increased resolution for winter and spring.

Fig.15. Fluorescence time series at increased resolution for winter and spring.

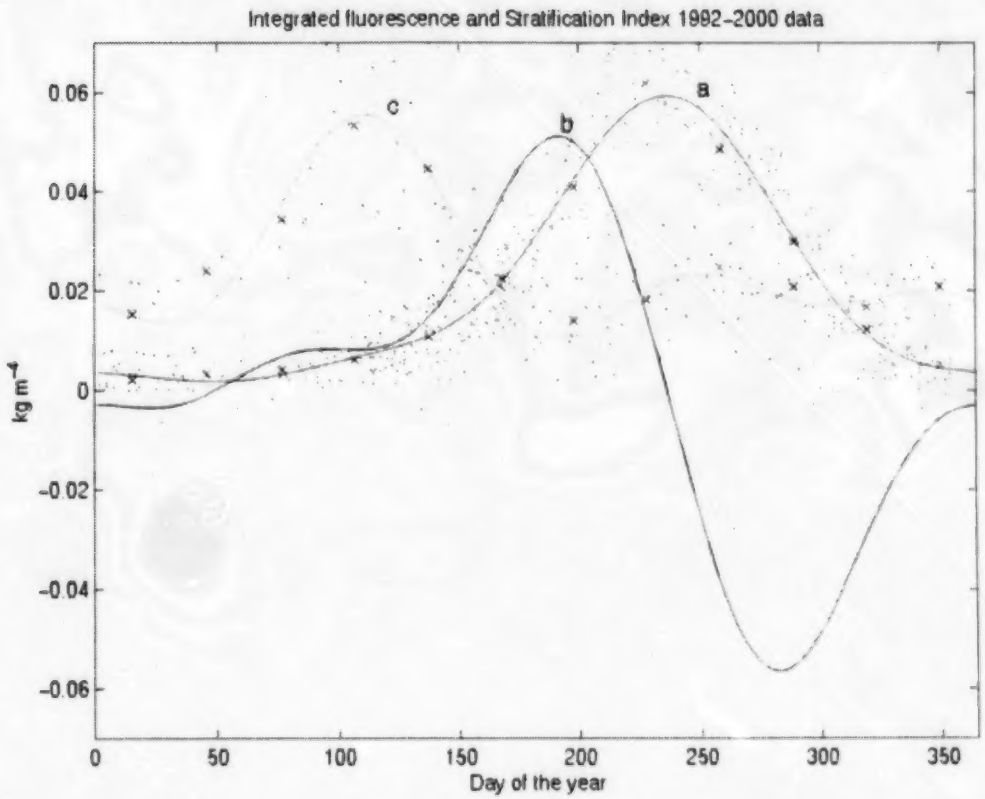

Fig.16. Stratification index (solid), the time derivative of stratification index (dashed) and integrated fluorescence (dotted) for data in the 1992-2000 period for Station 27. The scales for the derivative and fluorescence are relative. Small crosses show the values of the monthly mean stratification index and integrated fluorescence.

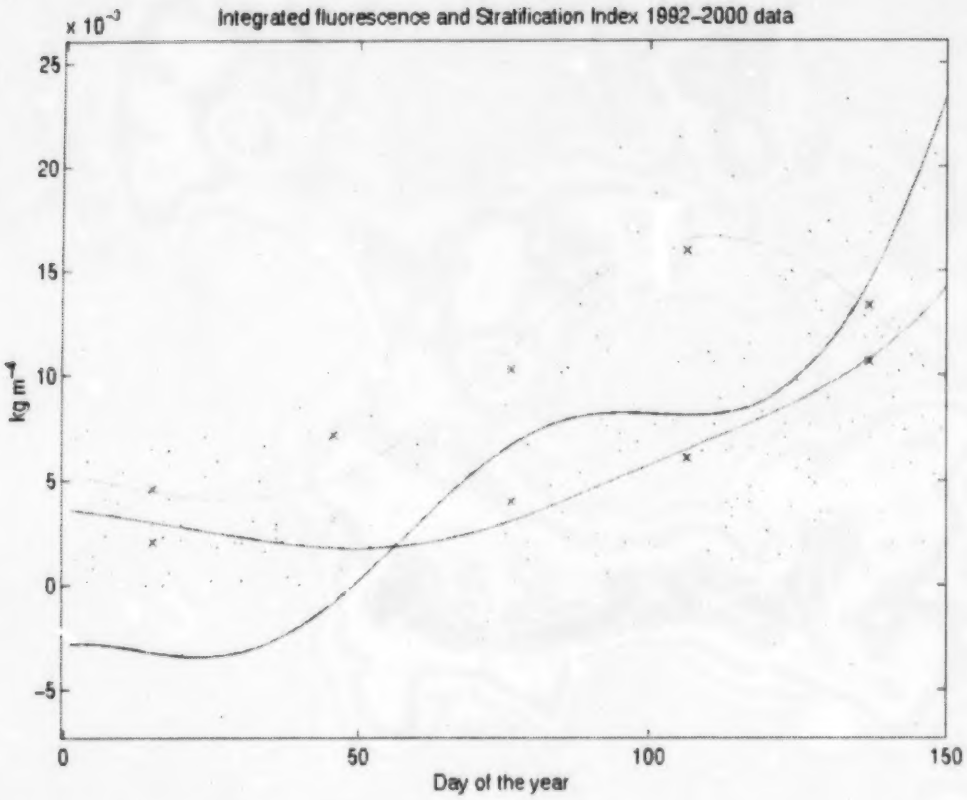

Fig.17. Expanded version of Fig.16 showing the timing of the spring bloom and onset of stratification.

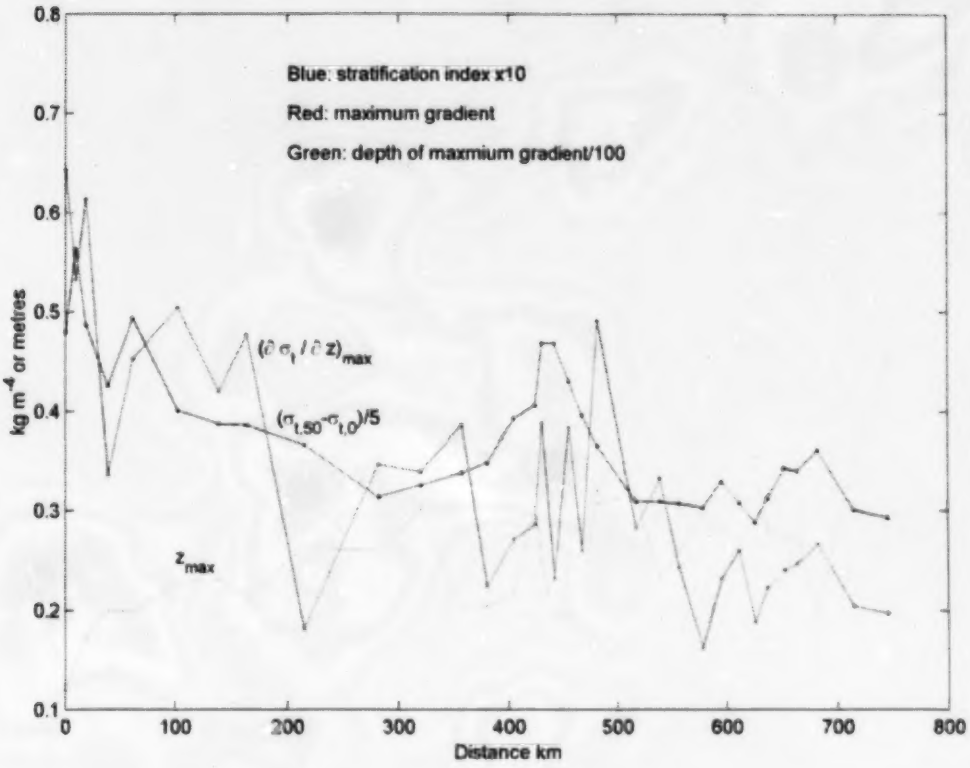

Fig.18. Stratification along the Flemish Cap transect. Stratification index (blue), value of the maximum density gradient (green) and depth of the maximum gradient. Values have been scaled to fit on the axes.

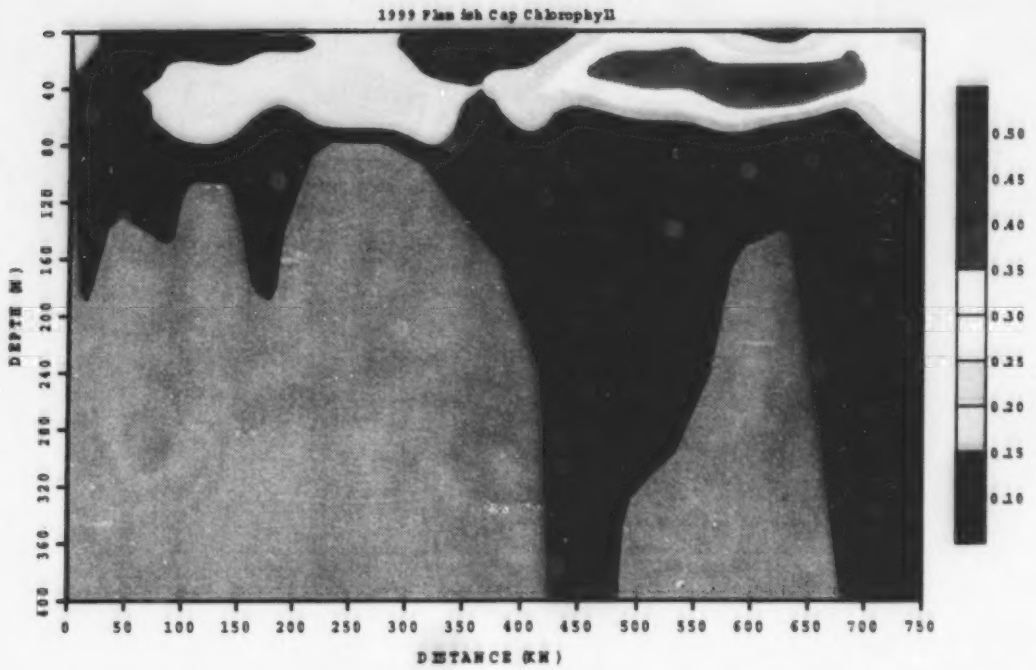

Fig.19. Fluorescence along the Flemish Cap transect.